

Mind the Gap: Tightening the Mass-Richness Relation with Magnitude Gaps

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ABSTRACT

We investigate the potential to improve optical tracers of cluster mass by exploiting measurements of the magnitude gap, m_{12} , defined as the difference between the r-band absolute magnitude of the two brightest cluster members. We find that in a mock sample of galaxy groups and clusters constructed from the Bolshoi simulation, the scatter about the mass-richness relation decreases by $\sim 15 - 20\%$ when magnitude gap information is included. A similar trend is evident in a volume-limited, spectroscopic sample of galaxy groups observed in the Sloan Digital Sky Survey (SDSS). We find that SDSS groups with small magnitude gaps are richer than large-gap groups at fixed values of the one-dimensional velocity dispersion among group members σ_v , which we use as a mass proxy. We demonstrate explicitly that m_{12} contains information about cluster mass that supplements the information provided by group richness and the luminosity of the brightest cluster galaxy, L_{BCG} . In so doing, we show that the luminosities of the members of a group with richness N are inconsistent with the distribution of luminosities that results from N random draws from the *global* galaxy luminosity function. As the cosmological constraining power of galaxy clusters is limited by the precision in cluster mass determination, our findings suggest a new way to improve the cosmological constraints derived from galaxy clusters.

Key words: cosmology: theory – galaxies: clusters – galaxies: evolution

1 INTRODUCTION

Galaxy clusters have long been exploited to probe the composition of the universe. The utility of galaxy clusters as cosmological probes using a broad range of techniques has been reviewed extensively by Allen et al. (2011). Galaxy cluster observations are a key component of any effort to constrain the cause of cosmological acceleration (see the review by Weinberg et al. 2012). Among many advances in cluster cosmology, modern optical surveys have enabled the construction of large samples of optically-identified clusters which, in turn, have led to competitive cosmological constraints from optically-identified cluster abundances (e.g., Gladders et al. 2007; Rozo et al. 2010).

Much of the constraining power of clusters results from determinations of their abundance as a function of their mass. The abundance of clusters by mass may be reliably predicted (e.g., Tinker et al. 2008), but cluster mass is not directly observable. Optical cluster cosmology efforts generally rely on using the number of cluster members (*rich-*

ness) as a proxy for mass to concurrently fit for cosmological parameters and the mass-richness relation (although see Newman et al. (2002) for another technique). In detail, richness must be defined precisely for the observational sample under consideration, so that the specific definitions of richness vary depending upon survey characteristics and cluster identification methods.

One way to improve cosmological constraints from optically-identified clusters is to reduce the scatter between the observable (richness) and the predicted quantity (mass) (Roza et al. 2010; Rykoff et al. 2012). In this paper, we suggest that the differences in absolute magnitude between the most luminous cluster members, data already contained within optical surveys aiming to perform cluster cosmology, can be harnessed to reduce the scatter in cluster mass for a fixed set of observables. Specifically, we show that *magnitude gap*, the difference in r-band absolute magnitude between the brightest and second brightest members of a galaxy group, can aid in the determination of group mass at both fixed

richness and fixed r-band luminosity of the brightest group member. We provide theoretical and observational support for this suggestion using the Bolshoi simulation of cosmological structure growth (Klypin et al. 2011) and galaxy group and cluster data from Data Release 7 of the Sloan Digital Sky Survey (SDSS) (Abazajian et al. 2009). In § 2 we describe mock galaxy catalogs constructed from the Bolshoi simulation. A brief description of the SDSS group data is given in § 3. We present results from our mock galaxy catalog in § 4 and from our analysis of the SDSS groups in § 5. We draw brief conclusions from these results in § 6.

2 SIMULATIONS & MOCK GALAXY CATALOGS

We use the Bolshoi N-body simulation (Klypin et al. 2011) to study the connection between magnitude gaps within galaxy groups and the mass-richness relation. Bolshoi models the growth of structure in a cubic volume $250 h^{-1} \text{Mpc}$ on a side within a ΛCDM cosmology with total matter density $\Omega_M = 0.27$, Hubble constant $h = 0.7$, power spectrum tilt $n_s = 0.95$, and power spectrum normalization $\sigma_8 = 0.82$. The Bolshoi data are available at <http://www.multidark.org> and we refer the reader to Riebe et al. (2011) for additional information. Our analysis requires reliable identification of self-bound subhalos within virial radii of distinct halos. We utilize the ROCKSTAR (Behroozi et al. 2011) halo finder in order to identify halos and subhalos within Bolshoi.

To connect the properties of galaxies to dark matter halos we employ the widely used subhalo abundance matching technique (SHAM) (e.g., Kravtsov et al. 2004; Conroy et al. 2006). We assume a monotonic relationship between the r-band luminosities of galaxies and the maximum circular speeds of test particles within their host dark matter halos, $V_{\text{max}} \equiv \max \left[\sqrt{GM(<r)/r} \right]$, where $M(<r)$ is the mass of the halo interior to the radial coordinate r . In broad terms, the reasoning behind this algorithm is that r-band luminosity is a rough proxy for stellar mass and stellar mass should correlate with the depth of the gravitational potential well, described by V_{max} . Subhalos evolve significantly due to interactions upon incorporation into a larger distinct halo, so V_{max} for subhalos may be a poor proxy for stellar mass or r-band luminosity. Conroy et al. (2006) demonstrated that a SHAM algorithm that assigns luminosities to subhalos based upon the maximum circular speed of the subhalo *at the time it merged with the distinct halo*, $V_{\text{max}}^{\text{acc}}$, can describe a broad range of galaxy clustering data from $z \approx 0$ to $z \approx 4$. We define the circular speed used in our luminosity assignment to $V_L = V_{\text{max}}$ for distinct halos and $V_L = V_{\text{max}}^{\text{acc}}$ for subhalos. We assign r-band luminosities to halos and subhalos through the implicit relation

$$n_g(> L) = n_h(> V_L), \quad (1)$$

where $n_g(> L)$ is the number density of observed galaxies with r-band luminosity $> L$ (Blanton et al. 2005) and $n_h(> V_L)$ is the number density of dark matter halos and subhalos with circular speed $> V_L$. Eq. (1) ensures that the distribution of luminosities assigned to dark matter halos and subhalos matches the observed luminosity function of galaxies. SHAM models of this kind successfully de-

scribe a variety of astronomical data (see Klypin et al. 2011; Trujillo-Gomez et al. 2011; Watson et al. 2012, and references therein).

Once brightnesses have been assigned to halos according to Eq. (1), we construct mock galaxy samples by imposing a brightness cut $M_r < -18$ on all the mock galaxies in Bolshoi. This brightness cut corresponds to $V_{\text{max}} > 92 \text{ km/s}$, well above the 50 km/s completeness limit of Bolshoi (Klypin et al. 2011). In this mock catalog, we consider galaxy groups to be collections of subhalos associated with the same host halo. We study the properties of these mock groups in § 4.

3 OBSERVATIONAL DATA

To study the mass-richness relation observed in low-redshift groups and clusters we use a volume-limited catalog of galaxy groups identified in Data Release 7 of the SDSS using the algorithm described in Berlind et al. (2006). This is an update of the Berlind et al. (2006) groups (based on SDSS Data Release 3) to SDSS Data Release 7. All of the members of this sample are members of the main galaxy sample of SDSS Data Release 7. The group catalog is constructed using a redshift-space friends-of-friends algorithm that has been corrected for incompleteness due to fiber collisions. The particular group catalog we use is constructed from galaxies in a volume-limited spectroscopic sample in the redshift range $0.02 < z < 0.068$ with r-band absolute magnitude $M_r - 5 \log h < -19$. We refer to this catalog as the “Mr19” group catalog. Each of the 6439 groups in the Mr19 catalog contains $N > 2$ members. We refer the reader to Berlind et al. (2006) for further details on the group finding algorithm.

4 PREDICTIONS FOR THE POTENTIAL UTILITY OF GAP INFORMATION

In this section we use the mock galaxy catalog described in § 2 to study the predictions of abundance matching for the dependence of host halo mass on galaxy group richness and magnitude gap. Such a study is idealized for several reasons, including the relative simplicity of the SHAM algorithm and the fact that groups can be unambiguously identified with halos of a particular mass. Nevertheless, this demonstration has the distinct advantage that the masses of the host halos in the Bolshoi simulation are known and do not need to be inferred imperfectly from observational data. To proceed, we define richness N as the number of mock galaxies within the host halo brighter than our specified absolute magnitude threshold. We take the magnitude gap to be the difference between the r-band absolute magnitude of the brightest galaxy within the halo and the second brightest galaxy within the halo, $m_{12} = M_{r,1} - M_{r,2}$, where $M_{r,i}$ is the r-band absolute magnitude of the i^{th} brightest galaxy in the halo.

We illustrate our motivation for exploring the utility of gap information in Figure 1, in which we plot the mass distributions of host halos in Bolshoi in a narrow range of richness, $12 < N < 18$. The gray, hatched histogram traces the mass distribution for *all* host halos in this richness range, while the thin red (thick blue) curve pertains to host systems

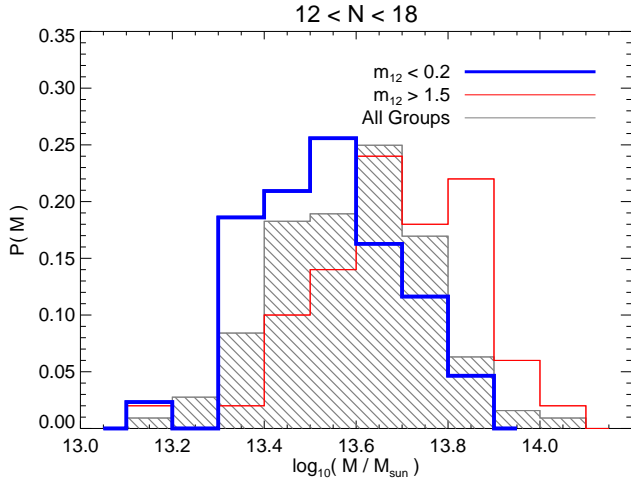


Figure 1. Plot of the mass distribution of host halos in Bolshoi in the richness range $12 < N < 18$. The mass distribution for all host halos in this richness range appears as the hatched, gray histogram. The thin red curve traces this distribution for the subsample of host systems with a very large magnitude gap ($m_{12} > 1.5$). The mass distribution of host halos with $m_{12} < 0.2$ is plotted with the thick blue curve. Note that most objects are not in either m_{12} bin traced by the red or blue histograms, which is why the full distribution plotted in gray does not resemble a combination of the red and blue. Evidently, large gap systems tend to be more massive at fixed richness, suggesting the possibility that m_{12} can be used to improve the calibration of the mass-richness relation.

with a large (small) magnitude gap m_{12} . Evidently, large gap systems tend to be more massive than their small gap counterparts at fixed richness. Of course the trend in Fig. 1 could simply be due to the finite width of the richness bin we have chosen, rather than following as a consequence of the mass-richness residual being correlated with m_{12} . To explore this issue more rigorously, we employ standard regression analysis techniques to find the linear relationship between $\ln(N)$ and $\ln(M)$ that minimizes $\sigma(\ln M)$. The use of a linear regression is well-motivated by previous results (for example, Becker et al. 2007) that find the mass-richness relation to be well-described by a power law. We find that our best fit model, $M_{\text{fit}}(N) = CN^\alpha$, with $C = 2.2 \times 10^{12} M_\odot$, and $\alpha = 1.1$, gives an accurate description of the mass-richness relation for the rich groups ($N \geq 10$) in our mock sample, yielding a mean residual $\langle \delta \ln M \rangle \simeq 0.02$, and a residual dispersion of $\sigma(\ln M) \simeq 0.33$.

In Figure 2 we plot the mean residual $\delta \ln M$ as a function of m_{12} . The trend suggested by Fig. 1 is borne out: groups and clusters with a large (small) magnitude gap m_{12} are more (less) massive than the average M at a given richness. A linear fit to the results illustrated in Fig. 2 indicates that $\delta \ln M \propto 0.18 m_{12}$, implying that there may be significant information about a cluster’s mass contained in the magnitude gap m_{12} that is not contained in the richness alone. Moreover, the mass-dispersion about the $m_{12} - N$ plane determined by a two-dimensional linear regression improves by 18% to $\sigma(\ln M) \simeq 0.27$, further demonstrating the potential improvement in mass determination provided by the use of magnitude gap information.

While the trend in the mass-richness relation with m_{12}

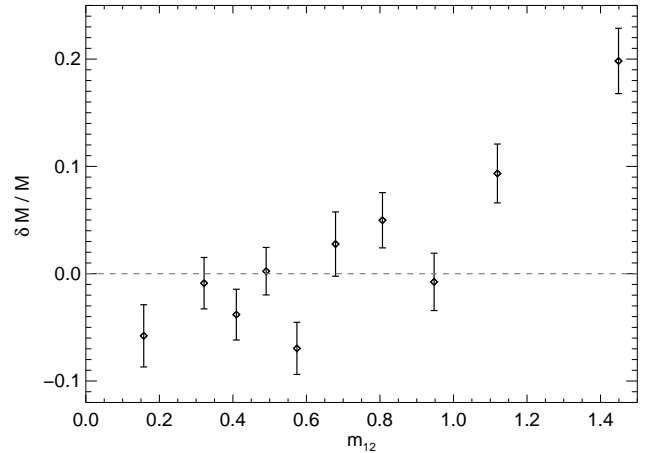


Figure 2. Plot of the residual $\delta \ln M$ of the best-fit mass-richness power law relation exhibited by groups and clusters in Bolshoi as a function of m_{12} . A linear fit to the residuals indicates that $\delta \ln M \propto 0.18 m_{12}$, suggesting that exploiting the magnitude gap may significantly improve cluster mass estimation techniques that rely only on richness.

as seen in Fig. 2 is the novel feature of this work, the tendency for large gap systems to be more massive at fixed richness appears in a variety of guises in the literature on *fossil groups*, which are typically defined to be galaxy groups with $m_{12} > 2$. The picture of fossil groups that is the most prevalent in the literature is that these are groups which assembled most of their mass at high redshift, so that processes such as dynamical friction and mass loss have had ample time to deplete these systems of their most massive satellite galaxies, leaving behind a very bright central galaxy with few comparably bright satellites (Jones et al. 2003; D’Onghia et al. 2005; Zentner et al. 2005).

In the above scenario for the origins of fossil groups, the same processes that lead to the formation of a large magnitude gap are also at work in the depletion of the number of group members above a given brightness threshold. In other words, this picture posits a dynamical connection between m_{12} and richness. However, even in the complete absence of such dynamical processes, we may still expect large-gap systems to have fewer members than small-gap systems. This is a consequence of the shape of the Schechter function: for any luminosity function $\Phi(L)$ with a slope that steepens with brightness, the average gap m_{12} obtained from a set of N random draws from $\Phi(L)$ increases as N decreases.

The extent to which dynamical processes influence the relationship between m_{12} and N remains an open question, but we point out here that if m_{12} were purely statistical, resulting from N random draws from a Schechter function, the magnitude gap would contain no information about mass that would not already be provided by knowledge of richness. This follows from Bayes’ Theorem. If m_{12} were determined strictly by N random draws from a common luminosity function, then $P(m_{12}|M, N) = P(m_{12}|N)$. Then it follows directly from Bayes’ Theorem that $P(M|N, m_{12}) = P(M|N)$; that is, the probability distribution of mass is unchanged by knowledge of m_{12} when the richness is known. This is sensible because in this scenario the m_{12} distribution is deter-

mined entirely by N , so knowledge of m_{12} provides no new, independent information about the system. Thus the trend exhibited by the mass-richness relation seen in Fig. 2 reflects a relationship between the magnitude gap and the mass of host halos in our mock sample beyond that expected from sampling a luminosity function a finite number of times.

The SHAM-based results presented in this section show that a simple and well-supported model for populating halos with galaxies makes a definite prediction for the relationship between halo mass, magnitude gap, and richness in groups. To be sure, there are many factors that will tend to wash out the clear trend seen in Fig. 2. For example, group/cluster membership (and hence, richness) is determined by halo membership, so contamination by interlopers due to projection effects is not included; the simulations do not suffer from edge effects that may alter the richnesses of groups in real surveys; and the fidelity with which the SHAM prescription for identifying halos and subhalos with luminous galaxies correctly describes richness has not been extensively tested in this context. As we will see in the next section, despite these complicating factors the dependence of the mass-richness relation on m_{12} appears to be significant in a spectroscopic sample of galaxy groups observed in SDSS.

5 THE OBSERVED CONNECTION BETWEEN MASS, RICHNESS, AND MAGNITUDE GAP

We now examine the mass-richness scaling relation seen in groups and clusters in the volume-limited Mr19 galaxy group catalog described in § 3. The principal result of this section appears in the bottom right panel of Figure 3, which we will argue demonstrates that the magnitude gap contains information about cluster mass that is independent from both richness and L_{BCG} . Most of the work described in this section, illustrated in the remaining three panels of Fig. 3, addresses a variety of possible systematics and selection effects that are germane to our primary conclusion.

As our mass proxy for the groups we use σ_v , the one-dimensional velocity dispersion of member galaxies, defined as

$$\sigma_v \equiv \frac{c}{1+z} \sqrt{\frac{1}{N-1} \sum_{i=1}^N (z_i - \bar{z})^2}, \quad (2)$$

where N is the number of group members, z_i are the redshifts of the member galaxies, and \bar{z} is the redshift of the (unweighted) group centroid. We are chiefly interested in determining whether the scaling of richness with σ_v changes when comparing samples of groups with different m_{12} , as is suggested by the results in § 4. Assigning m_{12} values to the groups requires some care due to complications presented by fiber collisions which affect $\sim 8\%$ of the galaxies in Mr19. Fiber collided galaxies in the Mr19 sample are assigned the redshift of their nearest neighbor on the sky. As a galaxy's redshift is used to infer its absolute magnitude, this can result in a large error in the inferred brightnesses of fiber collided galaxies. Thus if either the brightest member of the group (BCG) or the second-brightest member (which we denote below as the SBG for 'second-brightest galaxy') is fiber collided, the group will be assigned an erroneous value of

m_{12} . As the BCG in particular is likely to be found near the group centroid where the galaxy number density can be very large, this scenario is relatively common; we find that $\sim 2\%$ of the groups in Mr19 have either a BCG or a SBG that is affected by fiber collisions. We define m_{12} to be the magnitude difference between the two brightest non-fiber-collided galaxies in the group, but we note that all of our conclusions remain unchanged if we allow galaxies affected by fiber collisions to be used in the definition of the magnitude gap.

In the upper left panel of Figure 3 we plot the mean richness of galaxy groups in Mr19 as a function of σ_v . This panel illustrates the results of a calculation in which we have divided the Mr19 groups into logarithmically-spaced bins over the range $150 \text{ km/s} \leq \sigma_v \leq 350 \text{ km/s}$, and computed the mean richness in each bin. Evidently, large-gap systems do indeed appear to be less rich at fixed σ_v (mass) than small-gap systems. However, before drawing this conclusion we now address several possible selection effects and complicating factors that could influence this result.

Selecting groups with a large magnitude gap biases one to select groups with a luminous BCG. For example, the Mr19 galaxy sample contains no galaxies dimmer than $M_r = -19$, so selecting groups with $m_{12} > 1.5$ requires the BCG to have a brightness $M_r < -20.5$. Meanwhile, Reyes et al. (2008) suggested that BCG luminosity provides information on group mass that is independent of richness, so we must account for this bias to ensure that the magnitude gap provides information that is independent from the known correlation between mass and BCG luminosity.

We illustrate the differences in BCG luminosity induced by this selection in the lower left panel of Fig. 3, with the thin blue (thick red) histogram tracing $\Phi_{\text{BCG}}(L)$ for small-gap (large-gap) systems. The upper right panel of Fig. 3 is an illustration of the potential importance of this effect as BCG luminosity clearly informs the $\sigma_v - N$ relation of the SDSS galaxy groups. Systems with brighter BCGs are also richer at fixed σ_v . This trend has the sense that should be expected if L_{BCG} were determined by the brightest of N random draws from a fixed, global luminosity function (e.g., Paranjape & Sheth 2011). While there may be other, dynamical effects at work in galaxy groups that influence the correlation between L_{BCG} and group mass, such processes do not counteract the positive correlation between L_{BCG} and richness at fixed σ_v seen in our group sample. We will return to this issue shortly.

To account for bias from differences in the BCG luminosity distribution, we have drawn a random subsample of 1000 of the low-gap, $m_{12} < 0.2$, groups with a BCG brightness distribution that matches that of the large-gap, $m_{12} > 1.5$ groups. The magenta, hatched histogram in the bottom left panel of Fig. 3 shows $\Phi_{\text{BCG}}(L)$ of the resulting L_{BCG} -matched subsample of the $m_{12} < 0.2$ groups. The $\sigma_v - N$ scaling relation for the small-gap, matched-BCG systems is shown as the purple triangles in the upper left panel of Fig. 3. Eliminating any differences between the BCG luminosity distributions of low-gap and high-gap systems *increases* the disparity between the $\sigma_v - N$ relations of low- and high-gap groups, so m_{12} informs this relation in a manner that is independent from BCG luminosity alone.

We compare the $\sigma_v - N$ scaling relation for large-gap systems and their matched- L_{BCG} , small-gap counterparts

in the bottom right panel of Fig. 3. The principal result of our analysis in this section lies in the comparison between the red diamonds and magenta triangles: at fixed L_{BCG} , large-gap systems are under-rich relative to small-gap systems at fixed σ_v (mass). However, because of the natural correlation between m_{12} and N discussed in § 4, some care is required before interpreting the differences between these points as implying that large-gap and small-gap systems have intrinsically different mass distributions at fixed richness. The difference between the red diamonds and magenta triangles shows that $P(N|\sigma_v, m_{12}) \neq P(N|\sigma_v)$, or equivalently, $P(m_{12}|\sigma_v, N) \neq P(m_{12}|\sigma_v)$. This inequality would hold even in a universe in which m_{12} is determined solely by N random draws from a global luminosity function. Yet, as discussed in § 4, in such a universe the magnitude gap contains *no* information about cluster mass that is *independent* from richness. However, it is possible to show that the $\sigma_v - N$ scaling relations exhibited by the SDSS groups are distinct from the relations expected if m_{12} were solely determined by random selection from a global luminosity function.

We demonstrate that this is the case by contrasting the SDSS group data against the following Monte Carlo (MC) simulation. We draw a random galaxy group from our SDSS sample and assign the values of σ_v and N of this group to the “MC” galaxy group. We populate the MC group by drawing N galaxies from the global luminosity function of all the galaxies in the Mr19 group sample. We assign the MC group a value of m_{12} by taking the difference between the r-band absolute magnitudes of the brightest and next-brightest galaxies used to populate the MC group. We repeat this procedure 10^6 times to construct a sample of one million MC groups with the same group multiplicity function and $\sigma_v - N$ scaling relation as the Mr19 sample. The MC groups exhibit a correlation between m_{12} and N at fixed σ_v that is determined solely by the statistics of random draws from the global luminosity function. In the bottom right panel of Fig. 3, we plot the $\sigma_v - N$ scaling relation for MC groups with $m_{12} > 1.5$ with orange asterisks, and MC groups with $m_{12} < 0.2$ with black crosses. Both samples of MC groups have been selected so that their L_{BCG} distributions match that of the large-gap systems seen in the data, so that all the samples plotted in the bottom right panel have the same $\Phi_{\text{BCG}}(L)$.

The differences in richness at fixed σ_v between the large-gap and small-gap groups in the SDSS data are clearly more significant compared to their MC counterparts. Based on this exercise, we can conclude that the gap distribution is not determined solely by statistical effects, providing strong evidence that having a large magnitude gap is, in fact, correlated with being under-rich at a given mass. Moreover, because we have controlled for the brightness of the BCG, this implies that the magnitude gap m_{12} contains information about the masses of galaxy groups that is *independent* from *both* richness and BCG brightness. These results suggest that it may be possible to use m_{12} to improve optical estimators of group and cluster masses.

As a further check that the magnitude gap provides information that is independent from richness, we have supplemented the comparison of the Mr19 groups to the MC groups by comparing the m_{12} distribution of two subsamples of the Mr19 groups: one with $75 \text{ km/s} < \sigma_v < 150 \text{ km/s}$, and the other with $200 \text{ km/s} < \sigma_v < 400 \text{ km/s}$, both with

the same distribution of richnesses. We find that at fixed richness, the groups with larger velocity dispersion have a higher proportion of large m_{12} values relative to the small σ_v groups such that the mean m_{12} values of the two distributions are offset by $\sim 2.5\sigma$. The sense of this trend is in keeping with the results presented in Fig. 3. This result explicitly demonstrates that $P(m_{12}|\sigma_v, N) \neq P(m_{12}|N)$, directly implying that $P(\sigma_v|m_{12}, N) \neq P(\sigma_v|N)$, i.e., that the magnitude gap is informative about group/cluster mass even when the richness is known.

We conclude this section by addressing an additional possible systematic error in our data analysis. In our mock sample, the typical scatter in σ_v at fixed host mass is $\sim 15 \text{ km/s}$, and so we do not expect bin-to-bin scatter in mass to be a significant source of error. However, the two samples plotted in the bottom right panel of Fig. 3 have different richness distributions, and so their velocity dispersions σ_v are not determined with equivalent accuracy. In particular, as the error in σ_v depends upon N , this may induce systematic differences between the measurements of the velocity dispersion of the groups in the two samples, potentially producing a spurious difference in the $\sigma_v - N$ relation exhibited by small-gap and large-gap systems. To estimate the significance of this effect we have conducted the following exercise. For every group in each sample, we randomly select four members and use *only* these members to compute the velocity dispersion. We refer to the dispersion thus computed as the *reduced velocity dispersion*, σ_v^{red} . For the small-gap system we find that the slope of the $\sigma_v - N$ relation is slightly steeper than the $\sigma_v^{\text{red}} - N$ relation (as expected, since the σ_v^{red} measurements are generally noisier than σ_v estimates), but the trend with gap persists at similar levels and our conclusions remain unchanged: at fixed σ_v^{red} , groups with a large magnitude gap have fewer members than groups with small values of m_{12} .

6 SUMMARY & CONCLUSIONS

We have studied the improvement to group and cluster mass determination that may be reaped by exploiting the magnitude gap, m_{12} , between the two brightest group and cluster members in addition to group richness, N . After fitting the mass-richness relation in our mock sample of simulated groups and clusters with a power law, we find a significant correlation between the magnitude gap and group mass residual, $\delta \ln M \propto 0.18 m_{12}$. The strength of this correlation is significant when compared to the scatter about our power law fit, $\sigma(\delta \ln M) = 0.33$.

We see a similar trend in a volume-limited spectroscopic sample of galaxy groups observed in the SDSS. For group samples with different magnitude gaps, we find that large-gap groups have fewer members than small-gap groups at fixed σ_v . Reyes et al. (2008) recently suggested that using the luminosity of the BCG could aid in reducing scatter in cluster mass determinations. Similarly, we found that BCG luminosity is correlated with richness at fixed σ_v in our SDSS groups. By constructing appropriate random samples from the SDSS data, we were able to conclude that m_{12} contains information about group mass that is not contained in either richness or L_{BCG} .

Our findings are in conflict with recent results suggest-

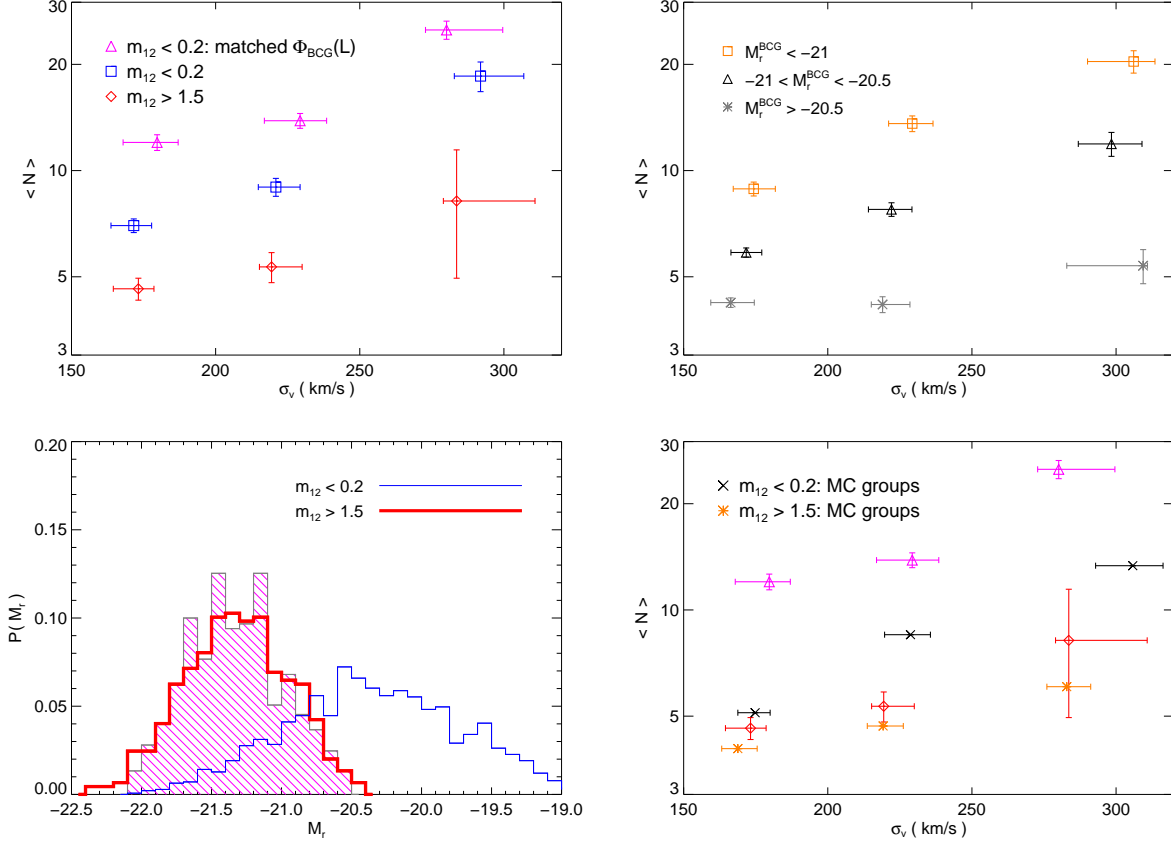


Figure 3. *Upper Left:* Richness as a function of mass proxy, σ_v . Points are placed at the median σ_v in each bin. Horizontal error bars represent the inner quartiles of the σ_v distribution in each bin. Vertical error bars show the error on the mean. Red diamonds show systems exhibiting a large magnitude gap $m_{12} > 1.5$, while blue squares show small-gap systems. The magenta triangles represent a randomly selected subsample of small-gap systems with a BCG luminosity function $\Phi_{\text{BCG}}(L)$, matched to that of the large-gap systems. *Lower Left:* Thick (Thin) histograms show the distribution of BCG luminosity $\Phi_{\text{BCG}}(L)$ (normalized to unit area) of large- (small-) gap systems in Mr19. The magenta, hatched histogram traces the BCG luminosity function of a random subsample of small-gap systems selected to match $\Phi_{\text{BCG}}(L)$ of the large-gap systems. *Upper Right:* Mean richness as a function of σ_v for galaxy groups with different BCG brightnesses. *Lower Right:* The $\sigma_v - N$ scaling relations for large-gap groups and small-gap groups. All samples have the same $\Phi_{\text{BCG}}(L)$. Orange asterisks and black crosses represent results from Monte Carlo (MC) simulation of the group population in a model assuming that gap does not explicitly depend upon σ_v (the group mass proxy). MC groups have negligible errors on the mean richness. Red diamonds and magenta triangles represent large- and small-gap groups in the SDSS data, as in the upper left panel. Differences between large-gap and small-gap groups in the data are significant compared to the MC groups, demonstrating that the magnitude gap m_{12} contains information about group/cluster mass that is *independent* from both richness and L_{BCG} .

ing that the distribution of magnitude gaps is determined purely by richness. Paranjape & Sheth (2011) find that the abundance of galaxy groups in Mr19¹ as a function of magnitude gap is consistent with the distribution resulting from a set of random draws from a global luminosity function, implying that group mass is only related to m_{12} through mutual covariance with richness. Meanwhile, Proctor et al. (2011) claim that the *fossil fraction*, defined as the fraction of groups with $m_{12} > 2$, is purely a reflection of the abundance of low-richness systems. In demonstrating that groups with different magnitude gaps exhibit different relationships between σ_v and richness we have established

that $P(m_{12}|\sigma_v, N) \neq P(m_{12}|N)$, explicitly showing that the magnitude gap is not strictly determined by richness.

We have demonstrated that, in principle, magnitude gap can inform cluster mass determination both in simple mock catalogs constructed from N-body simulations and in spectroscopic SDSS data; however, we leave the determination of the extent to which these relations may aid forthcoming cluster cosmology efforts as a subject of future work. Existing cluster cosmology samples differ from the group catalogs we have studied in several ways. For example, the maxBCG clusters (Koester et al. 2007) are selected using photometric (rather than spectroscopic) data with an independent algorithm that uses color and i-band luminosity criteria. Additionally, the maxBCG clusters extend to higher luminosities and larger richnesses than our groups. Forthcoming cluster cosmology efforts with data from imaging surveys like the Dark Energy Survey (DES) will likewise identify

¹ Note that the effective volume of the Mr19 galaxy group sample studied in Paranjape & Sheth (2011), which was based on SDSS Data Release 3, is less than half the effective volume of our Data Release 7-based Mr19 sample.

clusters using photometric data and probe larger richnesses. Moreover, the richnesses of maxBCG clusters are defined according to a more complex optimization procedure than the richnesses of our groups (Koester et al. 2007; Rozo et al. 2009). We have analyzed the Berlind et al. (2006) clusters because the cluster membership assignments for the maxBCG clusters are not publicly available. We do not anticipate the correlations that we point out here to be particularly strong functions of redshift or richness, but this will need to be tested more extensively both in mock catalogs and forthcoming data.

There are at least two distinct ways in which m_{12} may be exploited to tighten the relationship between group/cluster mass and richness. First, the magnitude gap could be treated on an equal footing with richness, so that rather than calibrating the mass as a one-dimensional function of richness one could instead treat the mass as a function of N and m_{12} simultaneously. Simulations coupled with detailed studies of extant and near-future data could provide parameterized forms for the $m_{12} - M$ relation with reasonable priors as they do now for the $N - M$ relation. We studied the potential benefit of this approach in our mock group sample by comparing the difference in the scatter about the residual mass estimation between a one-dimensional linear regression on richness and a two-dimensional linear regression on richness and magnitude gap. We find that the scatter in the residuals $\delta \ln M$ improves by $\sim 15 - 20\%$ when using a fit for mass as a function of N and m_{12} instead of N alone. While this improvement may seem modest, it comes at no additional observational cost, because the magnitude gap will always be available in the same data set used to measure the richness.

A second approach is suggested by the observation that the relationship between $\delta \ln M$ and m_{12} in our mocks appears to be nonlinear, with the systems with the very largest gaps appearing to be outliers in the mass-richness relation (see Fig. 2). The highest-gap systems have inordinately large masses at fixed richness. One may imagine utilizing gap information to identify significant outliers in the mass-richness relation. It may be possible to impose a cut on m_{12} and restrict consideration to groups and clusters with a modest magnitude gap ($m_{12} \lesssim 1.5$) to calibrate the mass-richness relation. This may be particularly helpful in photometrically-identified groups because interloper contamination will be more significant in the absence of spectroscopic redshifts, but interlopers can only *reduce* the magnitude gap, so large-gap systems will remain mass-richness outliers. Of course, the effect of any such cut on cluster abundance must be calibrated and accounted for, and this must be a subject for further work. In a forthcoming companion paper (Hearin et al. 2012, in prep), we study in detail the global abundance of groups and clusters as a function of m_{12} over a wide range of masses, providing precisely the information that would be required to carry out this second approach.

As we were preparing to submit this paper for publication, we became aware of another paper (Wu et al. 2012) that studies some of the same material that we have addressed. In particular, they focused on the host halo with the most extreme difference between the V_{\max} value of the host and its largest subhalo, the N-body simulation analog of a cluster with a very large magnitude gap. They found that this halo also appeared to be an outlier in many of

the host halo properties they studied, including the number of subhalos contained by the host. This finding appears to be in keeping with the second approach described above to using m_{12} in the calibration of the mass-richness relation.

However the calibration is conducted, our results suggest that the magnitude gap m_{12} contains information about cluster mass that is independent from both richness and L_{BCG} , the luminosity of the brightest cluster member. Exploiting this additional information to improve existing optical tracers of cluster mass may improve the constraining power of optically-identified galaxy clusters on cosmology.

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